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FINAL REPORT FOR
Origins Of Energetic Ions in the Earth's Magnetosheath
Contract NAS5-31213
(for the period ending 7 June 1994)

This final report describes activities under NASA contract NAS5-31213 to Lockheed Missiles and Space Company. The report covers the entire contract period from 8 May 1991 to 7 June 1994. This is a contract under the NASA Guest Investigator Program for the analysis and interpretation of the combined scientific data from the Hot Plasma Composition Experiment (HPCE) and the Charge Energy Mass (CHEM) spectrometer on the AMPTE/Charge Composition Explorer (CCE) spacecraft. These combined data sets have been used to survey the energetic ion environment in the Earth's magnetosheath to determine the origins and relative strengths of the energetic ion populations found there.

INTRODUCTION TO DATA ANALYSIS ACTIVITIES

A significant amount was accomplished during the first contract year for this analysis of energetic ion populations. Much of the work early in the first year centered around the development of computer code to analyze and interpret the combined CHEM and HPCE data sets. This code development was used as a means to become familiar with the CHEM data and the capabilities of the CHEM instrument.

In the second year of the contract, the codes developed in the first year were used in several studies of the magnetosheath, magnetopause, and associated layers. These studies have lead directly to papers either published or in press in the Journal of Geophysical Research (and other refereed Journals).

Finally, in the third year of the contract, the most important study to determine the relative strengths of the energetic ion populations in the magnetosheath was performed. This study also lead directly to a publication in the Journal of Geophysical Research. In the course of developing this study, required work on the various regions in the Earth's magnetosheath, including the plasma depletion layer were performed. This work supported several studies of the region that had direct impact on the final outcome of the energetic ion studies. Finally, the remaining time was spent studying the magnetopause itself in an effort to determine how ions cross this boundary.

DETAILED SUMMARY OF ACCOMPLISHMENTS

Appendix A is a listing of the presentations made to the scientific community under this contract. Appendix B is a chronological listing of the 14 publications submitted to scientific journals under this contract. This second appendix contains the bulk of the work under this contract and this section will summarize the efforts of each of the publications. The summary will be made in chronological sequence.

1. Engebretson, M. J., D. L. Murr, K. N. Erickson, R. J. Strangeway, D. M. Klumpar, S. A. Fuselier, L. J. Zanetti, and T. A. Potemra, The spatial extent of radial magnetic pulsation events observed in the dayside near synchronous orbit, *J. Geophys. Res.*, 97, 13,741-13,758, 1992.

Contributions to this paper came from testing of the newly developed code to determine the moments from the CHEM instrument. In this study, we used AMPTE/CCE data as well as data from other spacecraft to investigate the radial and longitudinal extent of magnetic pulsation events in the magnetosphere with predominantly radial polarization. Of importance in this study was the determination of the local plasma beta during the wave events. This was accomplished by using the AMPTE/CCE HPCE instrument to determine the plasma beta of the low energy plasma and the CHEM instrument to determine the plasma beta of the energetic ring current plasma. In establishing the mechanism for wave generation, it was important to observe that there was no correlation of wave onset or amplitude with plasma beta. This eliminated the possibility of an external source to drive the waves and pointed instead to a local field aligned resonance instability leading to wave growth.

2. Fuselier, S. A., Energetic magnetospheric protons in the plasma depletion layer, *J. Geophys. Res.*, 97, 13,759-13,766, 1992.

This paper, along with the follow-on study comparing two magnetosheath regions, is one of the more important papers produced under this contract. Interplanetary magnetic field line draping against the magnetopause causes the formation of a plasma depletion layer near the subsolar region. The properties of this layer were being thoroughly investigated partially under another contract. However, it was realized that the conditions for formation of the layer, namely quasi-perpendicular bow shock conditions in the subsolar region, would lead to a unique conditions which would allow the investigation of magnetospheric leakage without the encumbrance of the other sources of energetic ions. This is because the quasi-perpendicular conditions in the subsolar region move the quasi-parallel bow shock well around the flanks of the magnetopause. Therefore, when the CCE spacecraft was in the plasma depletion layer in the subsolar region, it would be on

field lines that passed very close to the magnetopause. These are prime conditions for magnetospheric leakage. Furthermore, with the quasi-parallel conditions well around the flanks, this leakage could be observed without interference from the energetic ions accelerated at the Earth's quasi-parallel bow shock.

The paper outlines the study of 13 plasma depletion events observed in 1984 and 1985 by the CCE spacecraft. Combined HPCE and CHEM proton spectra are presented for the first time for these events. The proton spectra in the depletion layer were found to be similar to those in the adjacent magnetosphere (the presumed source region). Furthermore, the densities were compared to typical densities for energetic ions upstream from the bow shock. In this comparison, it was found that the leaked ions would probably contribute on the order of 10% of the total upstream energetic ion density in the energy range from 10 to 100 keV/e. However, a detailed comparison was postponed for the subsequent paper (paper 5 in this list).

3. Fuselier, S. A., E. G. Shelley, and D. M. Klumpar, Mass density and pressure changes across the dayside magnetopause, *J. Geophys. Res.*, 98, 3935-3942, 1993.

This paper has important implications on the magnetopause boundary. Using observations from AMPTE/CCE, the changes in mass density from the magnetosheath to the low latitude boundary layer are determined for 27 magnetopause crossings. In this study, we determined the contributions to the low latitude boundary layer from the major ion species present there (H^+ , He^{2+} , He^+ , and O^+). The important result was that the solar wind protons dominated the mass density nearly always. Contributions to the total pressure were also determined. To do this, we had to combine the HPCE and CHEM data to make sure that we included the more energetic portion of the magnetospheric ion distributions. Again, the solar wind proton distribution dominated the pressure in the LLBL.

Another important result from this study was that, because the solar wind protons dominated the LLBL density, the conservation of mass density across a time dependent rotational discontinuity was not found to hold locally. This conservation law was assumed to hold by several investigators prior to this paper. The paper outlines the "missing mass" in the LLBL and the implications of the study. Further research on this important topic is needed to determine why the conservation law does not hold.

4. Denton, R. E., M. K. Hudson, S. A. Fuselier, and B. J. Anderson, Electromagnetic ion cyclotron waves in the magnetosheath plasma depletion layer, *J. Geophys. Res.*, 98, 13,477-13,490, 1993.

This paper is one of several investigating the properties of the plasma depletion layer. It was very important to establish these properties because the plasma depletion layer was used directly to

investigate the origin of energetic ions in the Earth's magnetosheath. In this paper, we used plasma data from a single magnetopause crossing to investigate the wave properties in the depletion layer. This required accurate accounting of the proton distribution in the layer and therefore a combination of the lower energy HPCE and the higher energy CHEM data. By modeling the proton distribution as a sum of Maxwellian distributions for the low and high energy parts, we were able to show that electromagnetic ion cyclotron wave growth in the plasma depletion layer was the result of temperature anisotropies in the low energy portion of the proton spectrum. Properties of these waves predicted from these calculations agreed well with observations. Furthermore, we began to establish a link between the waves and the temperature anisotropy which would later lead us to conclude that the waves were controlling the local plasma parameters in the plasma depletion layer.

5. Fuselier, S. A., A comparison of energetic ions in the plasma depletion layer and the quasi-parallel magnetosheath, *J. Geophys. Res.*, 99, 5855-5868, 1994.

This paper is a follow-on to paper #2. It greatly expands the survey of the energetic ions to include a comparison of the energetic ions in the plasma depletion layer with those in the quasi-parallel magnetosheath. The identification of the quasi-parallel magnetosheath is described in paper 6 and paper 11. Using the procedure outlined in paper 2, the densities, temperatures, and flow velocities of the energetic ions in both regions were determined. Included in this study were the energetic He²⁺, which turns out to be an important component of the study. This paper completed the major portion of the study under this contract. In it, the relative contributions of the magnetospheric and bow shock sources of energetic ions are determined unambiguously for the first time. The quasi-parallel shock provides the majority of the energetic protons, with an upper limit of 35% for the magnetospheric source. For He²⁺, the disparity is much greater, with the bow shock source providing essentially all of the energetic ions. Of course, these percentages were for the energy range from 10 to about 100 keV/e. However, over 99% of the energetic ion density is contained in this energy range. Finally, with the energetic ion sources properly quantified, the relative acceleration efficiency of protons and He²⁺ was determined. This parameter is important for all shock research up to and including astrophysical shocks such as supernova shocks. It was found that the bow shock accelerates He²⁺ about 2 to 3 times more efficiently than protons.

6. Anderson, B. J., S. A. Fuselier, S. P. Gary, and R. E. Denton, Magnetic spectral signatures in the Earth's magnetosheath and plasma depletion layer, *J. Geophys. Res.*, 99, 5877-5891, 1994.

In this paper, the important regions of the Earth's magnetosheath are identified using wave and particle data. These regions include the plasma depletion layer and the magnetosheath proper. This paper expands on previous work by showing there is a smooth transition from the

magnetosheath to the plasma depletion layer. Furthermore, it demonstrates the ordering between the plasma beta and the proton temperature anisotropy. This ordering is very important for overall magnetosheath properties. The ordering is expected by linear plasma theory of the electromagnetic ion cyclotron wave instability discussed in paper 7. In addition to this instability, the mirror mode is also active in the magnetosheath. Of critical importance in this paper was the division between the plasma depletion layer and the magnetosheath proper. This division came about only by using the higher energy ions as a tracer of the quasi-parallel and quasi-perpendicular magnetosheath.

7. Denton, R. E., S. P. Gary, B. J. Anderson, S. A. Fuselier, and M. K. Hudson, Low-frequency magnetic fluctuation spectra in the magnetosheath and plasma depletion layer, *J. Geophys. Res.*, 99, 5893-5901, 1994.

This paper quantifies the anisotropy beta relationship determined empirically in paper 6. Furthermore, it demonstrates that nearly the full range of wave phenomena observed in the magnetosheath is reproducible from linear theory. The anisotropy beta relationship is shown to result from a competition between the large scale magnetosheath depletion process, that tends to drive the anisotropy up and the local wave-particle interactions that tend to keep the anisotropy near threshold of the instability.

8. Denton, R. E., B. J. Anderson, S. P. Gary, and S. A. Fuselier, Bounded anisotropy fluid model for ion temperatures, *J. Geophys. Res.*, 99, 11,225-11,241, 1994.

This paper contains one of the more important results to come out of the magnetosheath research under this contract. Using the anisotropy beta relationship found empirically in paper 6, this paper illustrates how this relationship leads to an accurate description of the temperature variations in the magnetosheath. The predicted temperature evolution not only agrees well with the observations, it indicates that other temperature variations predicted by CGL theory or isotropic plasma theory are clearly inadequate in the magnetosheath. This important result points toward the possibility of doing an MHD simulation of the magnetosheath which accurately includes the anisotropy of the plasma.

9. Greenspan, M. E., D. C. Hamilton, B. J. Anderson, S. A. Fuselier, and E. A. Greene, A field-aligned ion beam observed in the magnetosheath during the February 8, 1986 magnetic storm, *COSPAR STEP symposium proceedings*, in press, 1994.

This paper presents a case study of O⁺ and H⁺ in the magnetosheath for a well documented compression of the magnetosphere due to a large magnetic storm. One of the surprising features about this event was that the phase space density in the O⁺ beam in the magnetosheath was much smaller than the density in the adjacent magnetosphere. This suggests that the beam was accelerated out of the magnetosphere. The paper concludes with a discussion of the possible mechanisms for energetic ions in the magnetosheath. The composition clearly points to a

magnetospheric source in this case. However, this case may be the result of merging instead of magnetospheric leakage.

10. Denton, R. E., B. J. Anderson, S. A. Fuselier, S. P. Gary, and M. K. Hudson, Ion anisotropy driven waves in the Earth's magnetosheath and plasma depletion layer, in *Solar System Plasma Physics: Resolution of Processes in Space and Time*, *Geophys. Monogr. Ser.*, in press, 1994.

This paper discusses and summarizes some of the results of the previous papers on the plasma depletion layer. In particular, it reviews the results of papers 6 and 7 and illustrates the strong linkage between the observations of ion cyclotron waves in the plasma depletion layer and linear theory of their generation. A single event is used to illustrate these points (as opposed to the larger statistical studies of Papers 6 and 7).

11. Fuselier, S. A., B. J. Anderson, S. P. Gary, and R. E. Denton, Inverse correlations between the ion temperature anisotropy and plasma beta in the Earth's quasi-parallel magnetosheath, *J. Geophys. Res.*, in press, 1994.

This paper is a follow-on study of paper 5. It uses the same data set in the study of energetic ions in the quasi-parallel magnetosheath to show that the thermal ion distributions in this region follow the same anisotropy-beta relationship as in the quasi-perpendicular magnetosheath. This is a very important result because it illustrates that the ion cyclotron wave interaction with the magnetosheath plasma extends throughout the magnetosheath. Thus, in modeling this region, the same anisotropy-beta relationship can be used as a closure relation throughout the magnetosheath. It is somewhat surprising that this is the case because the wave properties in the quasi-parallel and quasi-perpendicular magnetosheath are very different. However, we know from computer simulations that the important waves are the somewhat small amplitude ion cyclotron waves which can be effectively masked in the magnetic field data by larger amplitude fluctuations. Despite this, the efficiency of the cyclotron waves in scattering the ions allows them to maintain the plasma at marginal stability with only very low amplitude fluctuations.

12. Anderson, B. J., and S. A. Fuselier, Response of thermal ions to electromagnetic ion cyclotron waves, *J. Geophys. Res.*, in press, 1994.

This paper and the last 2 papers produced under this contract mark a shift in the study of energetic ion distributions in the magnetosheath. Since we have established the relative contributions of the two sources to the energetic ion spectrum in the magnetosheath, we turned to the specific mechanisms themselves. The shock acceleration mechanism is well studied and our contribution to this was the first measure of the relative acceleration efficiency of He^{2+} compared to H^+ . In these last three papers, we began a study of the magnetospheric leakage process. Very little is actually known about this process beyond simple models. These simple models can

reproduce the local time dependence of the magnetospheric leakage process but do little to produce an understanding of how magnetospheric ions cross the magnetopause. In this paper, we investigate some aspects of the magnetospheric ion distribution in the outer magnetosphere. In particular, we investigate how the magnetospheric proton distribution generates waves which heat the lower energy He⁺ distributions in the same region. Like the magnetosheath, we find that ion cyclotron waves are important in this process. Ion cyclotron waves generated by the proton anisotropy in the outer magnetosphere propagate up the magnetic field line until they reach a point where the wave frequency matches the local He⁺ cyclotron frequency. At that point, they heat the He⁺ distribution in the transverse direction. These heated ions move down the field line where they are observed in the equatorial plane by the CCE spacecraft. The process of heating off the equator leads to distinct He⁺ distributions. Further evidence that this is a resonant process comes from the fact that the protons are essentially unchanged from conditions when no cyclotron waves are present. This is true because the cyclotron wave frequency is always lower than the proton cyclotron frequency.

13. Fuselier, S. A., Kinetic aspects of reconnection at the magnetopause, in *Physics of the Magnetopause*, *Geophys Monogr. Ser.*, submitted, edited by P. Song, B. Sonnerup, and M. Thomsen, AGU, Washington D.C., 1994.

These next papers deal with the magnetopause and its boundary layers. It is clear that an understanding of ion leakage requires an understanding of this boundary. In this paper, we review the kinetic aspects of magnetic reconnection at the magnetopause. These aspects include ion reflection and transmission at the boundary. We show evidence of ion transmission across open magnetic field lines into the magnetosheath. This process is one of the two (including magnetospheric leakage) that allows magnetospheric ions to enter the magnetosheath. We review the distinct signatures of magnetic merging and show how they can be explained using very simple assumptions about the motion of individual ions in the magnetic and electric fields of the magnetopause current layer.

14. Fuselier, S. A., B. J. Anderson, and T. G. Onsager, Particle signatures of magnetic topology at the magnetopause: AMPTE/CCE observations, *J. Geophys. Res.*, submitted, 1994.

This final paper is very important for the further study of the process of magnetospheric ion entry into the magnetosheath. In this paper, we review the observed signatures of magnetic field topology using the AMPTE/CCE electron and ion distributions. The most important finding of this study is that the magnetopause is open more than 80% of the time even for conditions when the IMF is northward and the magnetic shear is small. This is significantly different from the current belief that northward IMF conditions do not support an open magnetopause. It has important

implications on the leakage of energetic ions across the magnetopause since this process was discounted early on by virtue of the fact that it was believed to be intermittent.

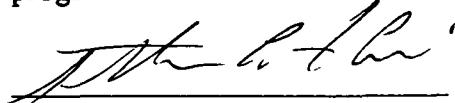
FUTURE WORK BEYOND THIS CONTRACT

Prior to this contract, there was no good estimate of the contribution to the magnetosheath energetic ion spectrum from the magnetospheric source. We now have a very good estimate of this contribution. Further study of this problem should now focus on the processes whereby the ions cross the magnetopause. Previous studies indicated that leakage due to finite gyroradius effects at the magnetopause and leakage across merged magnetic field lines were the processes that most likely allowed energetic ions to enter the magnetosheath. However, these studies tended to discount the merging process because it was felt that this was an intermittent process.

We now know from the results in paper 13 that the reconnection process is very important even when the shear at the magnetopause is small. This result indicates that magnetospheric ion entry into the magnetosheath along merged field lines must be occurring essentially all the time.

What is now needed is a comparison of these two processes to determine which is more important. It may turn out that both are important. To determine this, modeling of the process on a global scale is required. This modeling could be done rather simply using self-consistent electric and magnetic field models of the magnetosphere such as the source-surface model. By treating the energetic ions as test particles (we know now that they are relatively unimportant for wave processes in the sheath and magnetopause), we could build distributions in the sheath adjusting the conditions to allow and eliminate reconnection at the magnetopause. These results could be compared directly with observations published in the papers under this contract. In addition, the plasma depletion layer allows an interesting test of the merging and leakage models of magnetospheric ion escape. In this region, it is easy to tell from the electron signatures when the spacecraft is on merged field lines or simply on field lines draped against the magnetopause. Thus, the two processes can be compared directly.

This work requires additional funding not possible under this current contract. However, it remains an ideal topic for further study under the NASA Supporting Research and Technology program.



Stephen A. Fuselier

APPENDIX A: PRESENTATIONS

Lockheed Space Sciences Seminar 16 January, 1992, Palo Alto, CA.

Fuselier, S. A., Energetic ions in the Earth's magnetosheath and upstream region

University of Maryland Space Sciences Seminar 1 March, 1992, College Park, MD.

Fuselier, S. A., Energetic ions in the Earth's magnetosheath

American Geophysical Union Spring Meeting, Montréal Canada, 12-16 May, 1992.

Fuselier, S. A., Energetic magnetospheric protons in the plasma depletion layer (Abstract),
EOS Trans. Amer. Geophys. Union, 73(14), Spring Meeting Suppl., 250, 1992.

Shelley, E. G., S. A. Fuselier, and D. M. Klumpar, Mass density conservation across the
magnetopause (Abstract), *EOS Trans. Amer. Geophys. Union*, 73(14), Spring Meeting
Suppl., 256, 1992.

American Geophysical Union Spring Meeting, Baltimore, MD, May, 1993.

Fuselier, S. A., A comparison of energetic ions in the quasi-parallel magnetosheath and the
plasma depletion layer (Abstract), *EOS Trans. Amer. Geophys. Union*, 74(16), Spring
Meeting Suppl., 272, 1993.

Chapman Conference on Physics of the Magnetopause, San Diego, CA, March, 1993.

Fuselier, S. A., Particle reflection and transmission during reconnection.

APPENDIX B: PUBLICATIONS

Engebretson, M. J., D. L. Murr, K. N. Erickson, R. J. Strangeway, D. M. Klumpar, S. A. Fuselier, L. J. Zanetti, and T. A. Potemra, The spatial extent of radial magnetic pulsation events observed in the dayside near synchronous orbit, *J. Geophys. Res.*, 97, 13,741-13,758, 1992.

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Denton, R. E., B. J. Anderson, S. P. Gary, and S. A. Fuselier, Bounded anisotropy fluid model for ion temperatures, *J. Geophys. Res.*, 99, 11,225-11,241, 1994.

Greenspan, M. E., D. C. Hamilton, B. J. Anderson, S. A. Fuselier, and E. A. Greene, A field-aligned ion beam observed in the magnetosheath during the February 8, 1986 magnetic storm, *COSPAR STEP symposium proceedings*, in press, 1994.

Denton, R. E., B. J. Anderson, S. A. Fuselier, S. P. Gary, and M. K. Hudson, Ion anisotropy driven waves in the Earth's magnetosheath and plasma depletion layer, in *Solar System Plasma Physics: Resolution of Processes in Space and Time*, *Geophys. Monogr. Ser.*, in press, 1994.

Fuselier, S. A., B. J. Anderson, S. P. Gary, and R. E. Denton, Inverse correlations between the ion temperature anisotropy and plasma beta in the Earth's quasi-parallel magnetosheath, *J. Geophys. Res.*, in press, 1994.

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Fuselier, S. A., Kinetic aspects of reconnection at the magnetopause, in *Physics of the Magnetopause*, *Geophys. Monogr. Ser.*, submitted, edited by P. Song, B. Sonnerup, and M. Thomsen, AGU, Washington D.C., 1994.

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